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Sloshing Displacements of an Above Ground Cylindrical Liquid Storage Tank Subjected to a Near-Fault Earthquake Ground Motion

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ABSTRACT: Aboveground liquid storage tanks are critical components of infrastructure systems which are widely used to store chemicals, fuel and water. Field reports from past earthquakes indicate that these structures are quite susceptible to earthquake related damages due to sloshing effects of the contained liquid and that their failure can result in catastrophic damages to the environment in addition to significant financial losses. Earthquakes can damage liquid storage tanks in several ways. Hydrodynamic forces and the overturning moments acting on the tank wall due to the impulsive component of the liquid motion can result in the failure of the tank wall and the tank foundation. Excessive sloshing displacements which are primarily due to the long period convective component of the liquid motion can result in the spilling of the contained liquid or induce damages to the tank roof. This paper focuses on the sloshing response of a liquid storage tank subjected to near-fault earthquake strong ground motions with large displacement and velocity pulses which can be particularly destructive for structures with long vibration periods. In this study, the maximum sloshing displacements of a liquid storage tank subjected to a horizontal base excitation of a near-fault earthquake ground motion were analyzed with the ANSYS/Fluent and the CFD analysis results were post-processed with the help of Matlab image processing tools. Temporal variation of the sloshing displacements obtained from the CFD analysis was compared with the sloshing displacement time-histories obtained from the mass-spring equivalent models which are widely used in the design of liquid storage tanks.

Keywords: Sloshing, Near-Fault Earthquake Ground Motion

1 INTRODUCTION

Aboveground liquid storage tanks are critical components of infrastructure systems which are widely used to store chemicals, fuel and water. Field reports from past earthquakes indicate that these structures are quite susceptible to earthquake related damages due to sloshing effects of the contained liquid and that their failure can result in catastrophic damages to the environment in addition to significant financial losses [1-8].

Earthquakes can damage liquid storage tanks in several ways. Hydrodynamic forces and the overturning moments generated by the movement of the contained liquid can cause the failure of the tank wall or the tank foundation. Excessive sloshing displacements can result in the spilling of the contained liquid or induce damages to the tank roof [9].

This paper focuses on the sloshing response of a liquid storage tank subjected to near-fault earthquake strong ground motions with large displacement and velocity pulses which can be particularly destructive for structures with long vibration periods. In this study, the maximum sloshing displacements of a liquid storage tank subjected to a horizontal base excitation of a near-fault earthquake ground motion were analyzed with the ANSYS/Fluent and the CFD analysis results were post-processed with the help of MATLAB image processing tools. Temporal variation of the sloshing displacements obtained from the CFD analysis was compared with the sloshing displacement time-histories obtained from the mass-spring equivalent models which are widely used in the design of liquid storage tanks.

2 MODELING OF LIQUID STORAGE TANKS

Poor performance of liquid storage tanks on the 1960 Chile and 1964 Alaska earthquakes has motivated research on developing realistic modeling methods for their analysis and design. In early 1960s, Housner developed a mechanical analogue model for the liquid storage tanks with rigid walls and fixed base subjected to a horizontal base motion [10]. In Housner's model, continuous liquid medium is represented with a rigid mass at the bottom of the tank which moves in unison with the tank wall and convective masses which are connected to the tank with springs. The rigid mass primarily contribute the hydrodynamic pressures acting on the tank wall whereas the convective masses account for the sloshing displacements. Usually, a single convective mass which corresponds to the first convective mode is considered sufficient in setting up the mechanical model of the liquid (Figure 1). The magnitudes and the heights of the rigid and convective masses, as well as the stiffness of the springs required in setting up the analogue model can be obtained from charts and equations described in Housner's paper [10].

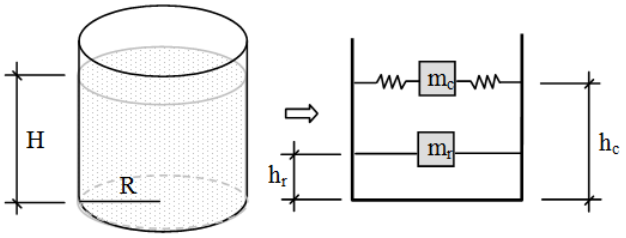

Figure 1. Housner's Mechanical Analogue Model for Liquid Storage Tanks with Rigid Walls Subjected to Horizontal Base Motion

Since 1960s, other mechanical analogue models have been developed in order to take into account various factors that affect the design and analysis of tanks such as the flexibility of the tank wall [11-14]. Mechanical analogue models considerably facilitate the analysis of the liquid storage tanks and accordingly, current design codes use one or more of these models for the prediction of the hydrodynamic forces acting on the tank wall and foundation as well as the maximum sloshing displacement which is required to determine the freeboard height [15-25].

Although, mechanical analogue models provide reasonable estimates for the hydrodynamic actions in liquid storage tanks, there are certain limitations to their use such as the restrictions on tank geometry due to the assumptions used in derivation of these models. Therefore, other modeling and analysis approaches such as FEM, FDM and SPH may have to be utilized in order to analyze the seismic response of arbitrarily shaped containers or to examine the free surface displacements when large sloshing displacements are expected. Literature reviews of the analytical and numerical methods used in the analysis of liquid storage tanks subjected to acceleration can be obtained from [26-28].

3 NUMERICAL STUDY

In the numerical study, maximum sloshing displacements of a tall Naphtha storage tank with a liquid height of 15 m and a radius of 5m subjected to horizontal strong ground motion with near fault characteristics was analyzed with the finite element analysis software ANSYS FLUENT [29] as well as a MATLAB script which uses the mechanical analogue models of Veletsos [13] and Chalhoub and Kelly [30]. The mathematical treatments of the sloshing displacements for these models are extensively described in their respective references and have not been repeated herein for the sake of brevity. A verification study of the MATLAB Script used in the study is presented in [31].

Ground acceleration history record (YPT060) of the 1999 Kocaeli (Turkey) earthquake obtained from the Yarimca Station (located approximately 2.6 km away from the fault rupture) was used in the numerical study. The acceleration time history of the ground motion was obtained from the PEER Strong Motion Database (http://peer.berkeley.edu/smcat) and the peak values of acceleration, velocity and displacement are presented in Table 1.

Table 1. Peak values of the acceleration, velocity and displacement of the earthquake ground motion used in the numerical study

Ground Motion	*PGA (g)*	*PGV (cm/s)*	*PGD (cm)*
Kocaeli Earthquake 1999 Yarimca Station (YPT 060)	0.268	65.7	57.01

The model geometry and the finite element mesh (Figure 2) of the liquid storage tank were created with the ANSYS Design Modeler and ANSYS Mesh Generator, respectively. Inflation layers were applied to the tank wall in order to more accurately predict the response at the boundary layer.

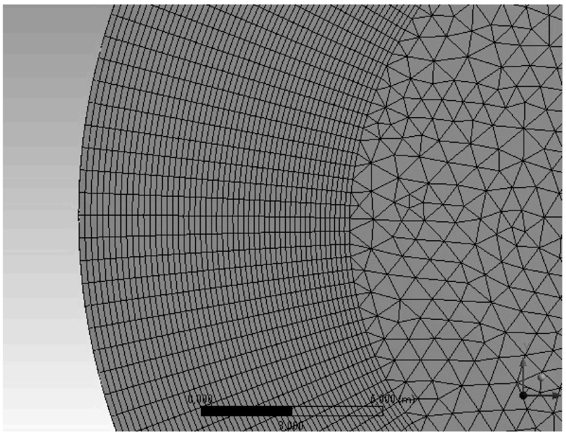

Figure 2. Finite Element Mesh of the Tank Wall

Boundary conditions of the FLUENT mesh are presented in the Figure 3.

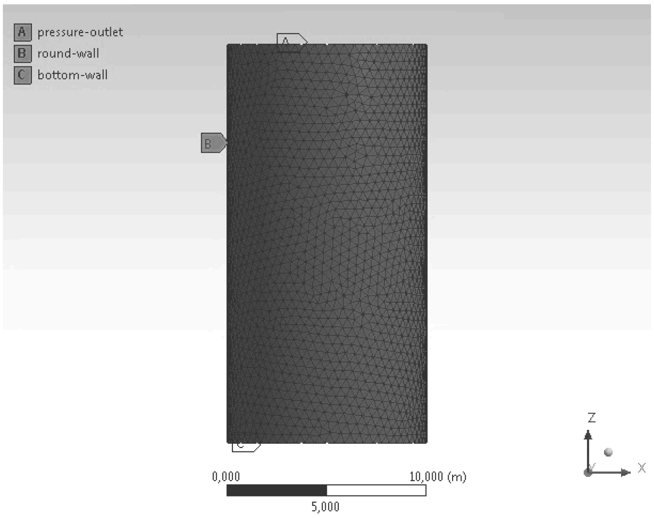

Figure 3. Boundary Conditions of the FLUENT Mesh

Motion of the tank was simulated by moving the side walls with a UDF which uses the velocity time-history of the earthquake ground motion. The solver options used in analyzing the sloshing displacements of the liquid are presented in Table 2.

Table 2. ANSYS FLUENT Analysis Parameters

Analysis Options	*Properties*
Solver Type	Pressure Based
Time	Transient (Step Size: 0.001s)
Model	Multiphase – Volume of Fluid
	Primary Phase: Air
	Secondary Phase: Naphtha
Turbulence Model	Viscous
	Realizable k-ε
	Standard wall function
Solution Method	PISO
	Skewness Correction:1
	Neighbor Correction:1
Spatial Discretization	Gradient : Least Squares Cell Based
	Pressure : Presto!
	Momentum: First Order Upwind
	Volume Fraction: Geo-Reconstruct
	Turbulent Kinetic Energy: First order upwind
Transient Formulation	First Order Implicit

Post processing of the results is a vital issue in any CFD analysis. Monitoring of the temporal variation of a parameter such as the sloshing displacements at the side wall requires the saving of analysis results at small time intervals which results in excessive use of disk space, particularly in 3D CFD models with a large number of nodes and elements. The size of the analysis output data file is in the order of 150MB for each time step. Therefore, a disk space of approximately 900 GB is required to save the output data file at the end of each time step (0.005seconds) of an earthquake ground motion that lasts for 30 seconds.

Instead of saving the analysis results in each step, free surface profiles of the liquid were saved as image files and the MATLAB Image Processing Toolbox was used to extract the temporal variation of the sloshing displacements at the side walls. Examples to these image files and the free surface profiles are presented in Figures 4 and 5, respectively.

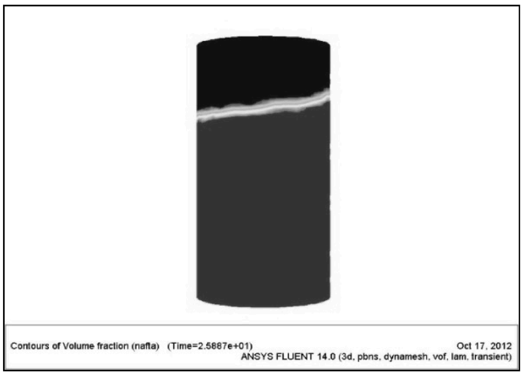

Figure 4. Sloshing Displacements of the Liquid

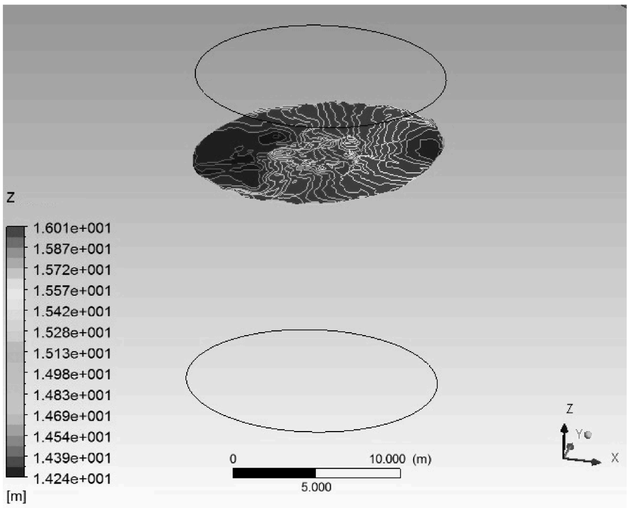

Figure 5. Free Surface Profile of the Sloshing Liquid

A comparison of the temporal variation of the sloshing displacement histories at the side wall is presented in the Figure 6.

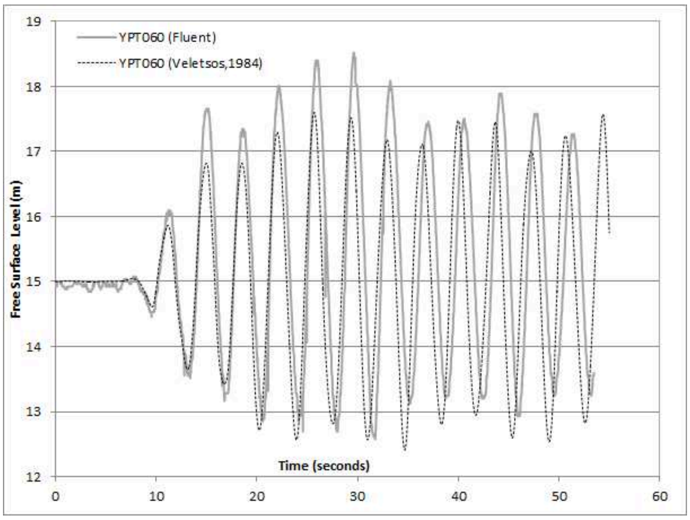

Figure 6. Temporal Variation of Free Surface Level

General variation of the sloshing displacements obtained from finite element analysis was quite similar to the one obtained from the mechanical analogue model. Although, calculated dips of the free surface displacement were almost identical for both cases, there were significant differences between the peak values of the free surface displacements. It was observed that sloshing displacements were quite high for each case. Calculated peak values of the sloshing displacements were 3.51 m and 2.60 m for the finite element and mechanical analogue models, respectively.

4 CONCLUSIONS

Mechanical analogue models are quite useful for making estimates of free surface displacements and hydrodynamic pressures acting on the tank wall. However, it should be considered that most mechanical analogue models are built on the assumptions of irrotational flow and small amplitude sloshing displacements. The difference of 0.91m between the predicted maximum values of free surface displacements for the finite element model and the mechanical analogue could be attributed to the large amplitude sloshing motion caused by the near fault ground motion.

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